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On the Detonability and Blast from Propylene-Oxide and Nitromethane Droplet-Air Clouds

By:

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Defence Research Establishment Suffield**

October 1997

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Suffield Memorandum No. 1499

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Abstract

This paper describes the results of experiments to assess the potential of fuel-air explosive (FAE) line charges in minefield breaching operations. The line charge consists of a 65-mm diameter hose filled with a liquid hydrocarbon and fitted with an internal detonating cord referred to as the "burster" charge. When the detonating cord is initiated, the hose fragments and the fuel is propelled outward to form a large droplet-air cloud. The cloud is detonated a short time later by a high-explosive "secondary" charge.

The detonability of propylene oxide fuel is first determined in a series of tests employing FAE canisters of nominal 3-litre volume. The critical mass of secondary charge for direct initiation of spherical detonation in a globally stoichiometric droplet-air cloud is found to be 10 grams of DM12 (85% PETN) explosive, indicating that propylene-oxide-air and ethylene-air have similar detonation sensitivities.

The results of line-charge trials show that the optimum ratio of fuel mass to burster charge mass (the F/B ratio) is about 50 and that an initiation time delay (Δt) of 150 ms is most satisfactory. The blast efficiency of the line charges in this study is about 40% based on a comparison between the measured and theoretically predicted positive impulses.

Equilibrium and numerical calculations indicate that higher detonation pressures are possible by replacing the propylene-oxide with more energetic nitromethane and by increasing the loading density of the cloud. In practice, this is achieved by using a smaller burster charge and a shorter initiation time delay. However, this gain in detonation pressure comes at the expense of lower impulses at locations of importance in a minefield breaching scenario. This result is not surprising given that our intention was to develop an explosive charge residing somewhere between HE and FAE in performance.

One practical problem with nitromethane line charges is that the initiation delay is so short that the cloud size varies substantially along its length at the moment of detonation. A rather novel line-charge design having a fuel dispersal charge and a separate travelling initiation charge is proposed as a remedy. However, in the single experiment performed, the droplet-air mass did not detonate as a result of the initiation charge being too small. Further study of this concept is warranted.

Acknowledgements

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Contractors played a key role in developing the line-charge technology described herein. David Weiss of Brome Laboratories Incorporated was responsible for the design and construction of a fast fuel filling system which performed reliably over the years until meeting its demise at the hands of an anti-tank mine. He also conducted a survey of commercial fire hoses suitable for this application. Paul Thibault and John Penrose of Combustion Dynamics Limited were responsible for the numerical modelling of detonation and air blast phenomena. The trial support provided by Gayle Hall was essential in our day-to-day progress.

Finally, the authors wish to thank personnel in the Directorate of Military Engineering (DMiE) for supporting the FAE work at DRES.

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ON THE DETONABILITY AND BLAST FROM PROPYLENE-OXIDE AND NITROMETHANE DROPLET-AIR CLOUDS

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1.0 INTRODUCTION

The Defence Research Establishment Suffield (DRES) has been engaged in explosive countermine studies since the early nineteen eighties. When the work first began, the requirement was to develop a means of rapidly breaching a safe lane through a field of simple, pressure-fuzed mines because these types of mines were thought to account for most of the global inventory of mines at the time. A fuel-air explosive (FAE) line charge was conceived and developed to address this requirement. The line charge is a propylene-oxide filled hose which contains an internal cord of detonating material known as the "fuel dispersal" or "burster" charge. Detonation of the burster charge results in the formation of a long fuel droplet-air cloud of approximately hemi-cylindrical cross section. Once formed, several high-explosive (HE) "secondary" charges, situated within the cloud at regular intervals along its length, are then detonated. These, in turn, initiate detonation of the cloud. The concept is shown in Figure 1 below.

The FAE line charge is an attempt to combine the attractive features of HE line charges and FAE canister systems. The former breaching apparatus, which includes the British "Giant Viper (GV)" and the American "Mine Clearing Line Charge (MICLIC)," is based on the detonation of a hose filled with high-explosive material such as C4 or aluminized PE6. Although it produces a continuous linear breach, the HE line charge is characterized by a blast field having regions of low impulse known as "skip zones." An additional disadvantage is that a significant fraction of the explosive material is oxygen which must be launched over the mined area despite its availability in the ambient air along the intended safe lane.

FAE canister systems, including the U.S. Army's "Surface Launched Unit Fuel-Air Explosive (SLUFAE)" system and its Navy sister, the "Catapult-Launched Fuel-Air Explosive (CATFAE)" system, do not suffer these shortcomings. In this approach, the fuel is distributed over a large area and mixed with ambient air prior to detonation. Although the result is a more uniform and higher specific impulse, a system based on rocket-launched canisters is both technically complex and expensive. As well, the use of overlapping circular clouds to approximate a lane results in the inefficient use of available fuel. The creation of an uninterrupted breach is also difficult to guarantee because the canister flight trajectories are sensitive to ambient wind conditions.

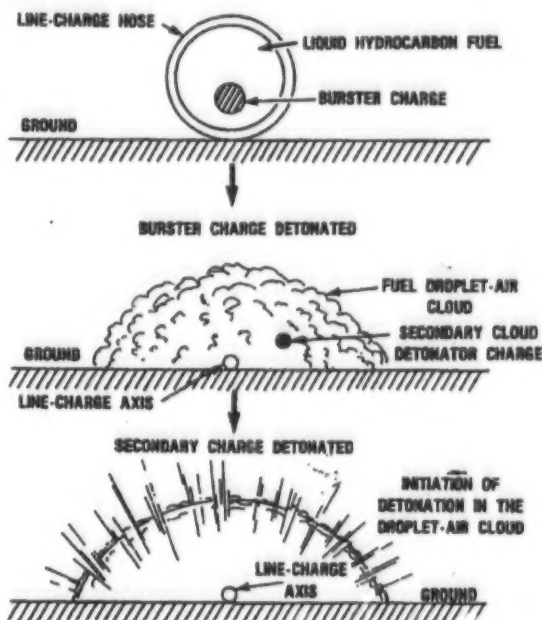


Figure 1: The fuel-air explosive line charge

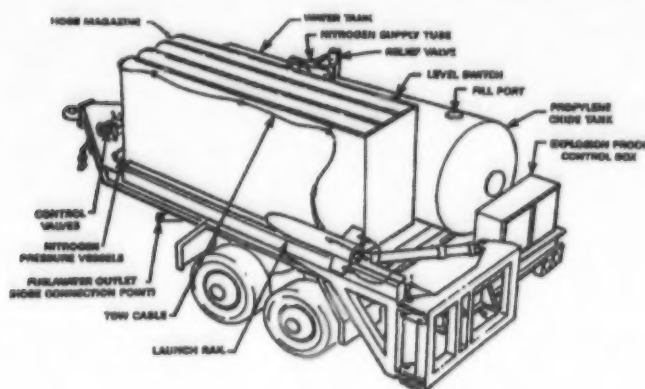


Figure 2: Schematic diagram of the FALCON minefield breaching system

a line-charge storage magazine, a rocket-powered ballistic tow vehicle, a cable assembly connecting the line charge to the tow vehicle, a storage tank containing propylene-oxide fuel, a storage tank containing water/anti-freeze solution, a fuel delivery system based on high-pressure nitrogen gas, an initiation system employing HE secondary charges, and hydraulic power and control/sequencing equipment. These components are mounted on a trailer, as shown in the schematic diagram of Figure 2.

During a breaching operation, the rocket-powered vehicle extracts the 300-m length of hose from the magazine. The hose is evacuated and contains only a 200-m long burster charge in the forward-most section. Once the flight assembly lands, the high-pressure nitrogen is used to pump propylene oxide from its storage tank into the first 200 metres of hose. The final 100-m length is filled with the water/anti-freeze solution to provide a safe standoff between the personnel/equipment and the explosive event. Immediately following the filling procedure, the burster charge is initiated to form the droplet-air cloud. Detonation of the cloud is brought about by three 1-kg secondary charges detonated 125 ms later. In its present state of development, FALCON is capable of executing the above-described operation in just over a minute.

This paper describes the results of canister tests and a series of line-charge tests conducted during the nineteen eighties in support of FALCON development. More recent tests to evaluate the feasibility of replacing the propylene oxide with a more energetic fuel (nitromethane) are also briefly described.

2.0 EXPERIMENTAL AND NUMERICAL RESULTS

2.1 Propylene-Oxide Canisters

The detonability of propylene-oxide droplet-air clouds was investigated in a series of trials employing cylindrical polyethylene canisters filled with fuel. The canisters were of 10 cm nominal diameter and measured 38 cm in height. They contained approximately 3 litres of fuel. Each canister was fitted with an axial burster charge consisting of a glass tube filled with 35 g of the military explosive DM12 (85% PETN). If the mass of the polyethylene and glass are included in the calculation of total propelled mass, the effective fuel-to-burster (F/B) mass ratio is just under 100. In previous studies^{2,3}, this value of F/B was found to produce clouds of globally stoichiometric

Premature ignition of the developing droplet-air clouds by the hot detonation products from neighbouring clouds has also been a problem.

The "Fuel-Air Line-Charge Ordnance Neutralizer," or FALCON, is an Advanced Development Model (ADM) of a minefield breaching system based on the above-described FAE line charge. It was conceived at DRES¹ and developed under contract by Canadian industry. The main components of the system include a 100-mm diameter line-charge hose containing an axial burster charge,

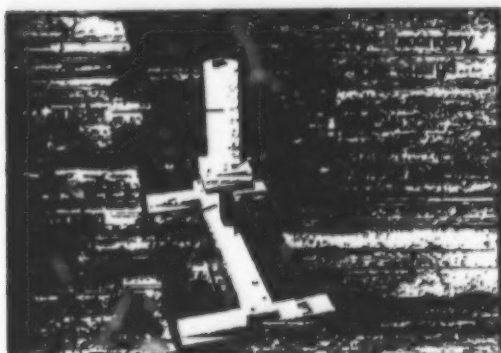


Figure 3: Photograph showing the canister and nearby secondary charge on a post

electronically controlled. This delay was arrived at by using cubed root scaling of the time delays found to be optimum in earlier studies^{2,3} employing 50-litre canisters. A photograph showing the test setup appears in Figure 3. The instrumentation consisted of high-speed cinematography and seven ground-level PCB piezoelectric pressure transducers placed in an array as shown in Figure 4.

The results of the trials are summarized in Table I. The data indicate that the critical charge mass for direct initiation of detonation in a globally stoichiometric, propylene-oxide, droplet-air cloud is 10 g of DM12 or about 8.5 g of PETN. This is only slightly larger than the 3.5 g tet.yl critical charge mass reported by Vanta et al.⁴ Experiments carried out by Murray et al.⁵ using disks of "Detasheet" explosive to initiate ethylene-air detonations have shown that the critical charge mass for a stoichiometric mixture lies between 9 g and 18 g. Given that only about two thirds of the Detasheet is energetic material (mostly PETN), the critical charge mass for this mixture becomes 9 ± 3 g of PETN. This means that the detonation sensitivities of propylene oxide and ethylene are very similar. Based on this conclusion, the critical tube diameter, D_c , for stoichiometric propylene-oxide-air is expected to be very close to that for stoichiometric ethylene-air. Moen et al.⁶ have reported the latter to be 43 cm. According to Murray et al.⁷, the critical thickness of a cloud resting on the ground is about one quarter of D_c or ~ 10 cm in this case.

The pressure and impulse data from the above-described tests are summarized graphically in Figures 5 and 6 below. The curves in the graphs are based on theoretical calculations for a 2-m radius, hemi-spherical, propylene-oxide, droplet-air cloud using the model proposed by Thibault and Otvos⁸ of Combustion Dynamics Limited. A hemi-spherical cloud of this radius has the same volume as the clouds observed in the experiments. In the model, the detonation states are first calculated using the NASA Lewis chemical equilibrium code developed by Gordon and McBride⁹. The blast field is then computed using a finite-difference code based on the Flux-Corrected Transport (FCT) algorithm of Boris¹⁰. In the calculations, the detonation conditions are imposed at the front as it is marched through the cloud at the appropriate detonation velocity. Initiation takes place at the origin. The model describes the data reasonably well. The lower experimental impulses in the near field are likely due to the shorter time required for the rarefaction wave to penetrate the actual "pancake" shaped clouds than that predicted by the model.

composition.

The canister was placed on a wooden stand in all tests. The secondary charge, which consisted of a sphere of DM12, was mounted on a nail on top of a post positioned 1 m away from the canister axis. Both the stand and the post were 30 cm in height. This arrangement guaranteed that the secondary charge would be immersed in the droplet-air mixture at a location about half the cloud radius away from the canister. Exploding bridgewire detonators (Reynolds RP-83) were used to initiate the charges. The time delay between burster charge and secondary charge detonations was set to 60 ms and was

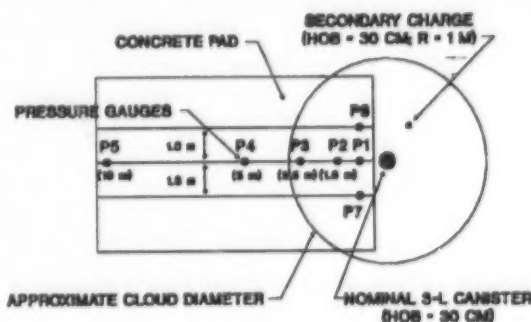


Figure 4: Transducer array for canister tests

Table I
Results of tests to determine the critical charge mass of DM12 explosive for direct initiation of propylene-oxide-air mixtures

Trial No.	Fuel Volume (l)	Burster Charge Mass (g)	Time Delay (ms)	Secondary Charge Mass (g)	Result
36-3	2.9	35	60	100	Detonation
36-4	3	35	60	50	Detonation
36-5	3	35	60	25	Detonation
36-6	2.9	35	60	10	Detonation
36-25	3	35	60	10	Detonation
36-28	3	35	60	9	Deflagration
36-27	3	35	60	8	Deflagration
36-26	3	35	60	5	Deflagration
36-7	3	35	60	RP-83 detonator	Deflagration

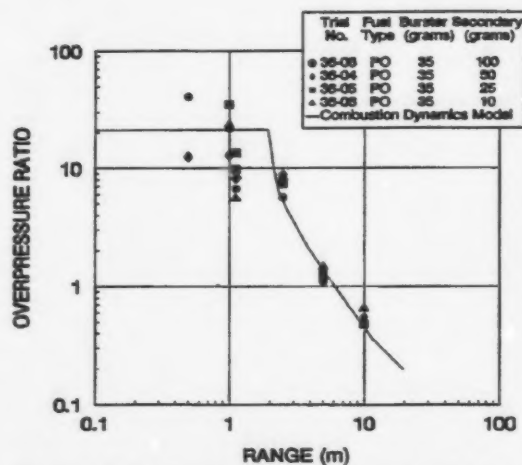


Figure 5: Overpressure versus range for 3-litre propylene-oxide canisters

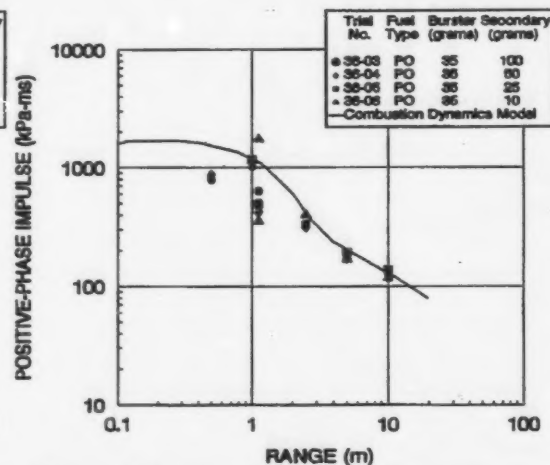


Figure 6: Positive-phase impulse versus range for 3-litre propylene-oxide canisters

2.2 Propylene-Oxide Line Charges

The setup for a typical line-charge test is shown in Figure 7. The line-charge hoses were of 65-mm nominal diameter and ranged from 15 to 61 metres in length. Several varieties of commercially-available industrial hose were investigated to assess their suitability for use in this application. Complete details are available elsewhere¹¹. Propylene-oxide fuel was used in most tests. However, the low vapour pressure fuel FFC (abbreviation for FFC002, a code-named U.S. fuel) was used in selected experiments. A fast fuel pumping system utilizing high-pressure nitrogen gas enabled the hoses to be filled at the rate of 5 m/s. The burster charges were configured from

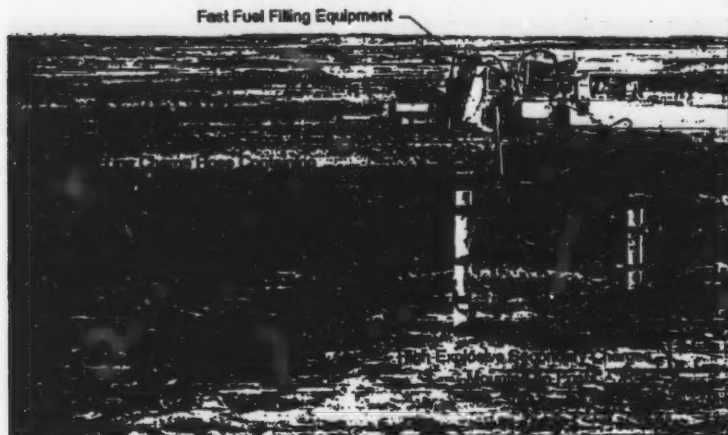


Figure 7: Photograph showing the setup for a typical line-charge test

commercially-available 60/40 TNT/RDX detonating cord. Both one-strand and two-strand burster charges having a total explosive mass between 32.0 g/m and 85.2 g/m were investigated. In tests where two strands of detonating cord were used, these were physically bound together.

Detonation of the cloud was achieved by a pair of high-explosive, DM12 secondary charges mounted on posts ranging in height up to 1 metre. These were detonated after

a time delay Δt between 100 and 200 ms from the commencement of fuel dispersal. The charge masses varied from 200 to 500 g. Large charges were used to increase the likelihood of initiating clouds of off-stoichiometric composition. Two charges were employed in most tests for redundancy. Both the fuel dispersal and subsequent explosion were monitored by high-speed cameras and an array of ground-level PCB pressure transducers laid out as shown in Figure 8.

Selected frames from an overhead cinematographic record, showing the development of a propylene-oxide, droplet-air cloud for a fuel-to-burster mass ratio of 87, are presented in Figure 9. The cloud in this case is approximately 10 m wide by 2 m high just prior to detonation of the secondary charges. As was the case for the FAE canisters, the "fuel" mass used in the calculation of F/B is the total propelled mass. The hose mass accounted for between 8 and 31 percent of the total propelled mass. It was necessary to include it in the calculation so that shot-to-shot comparison of the results would be possible.

Contour plots showing both the side-on and overhead history of the cloud prior to detonation appear in Figure 10. As expected, the ultimate cloud size is very sensitive to both F/B and Δt . This is emphasized in Figure 11 by the cloud height measurements from many of the tests. The two regions highlighted in the graph depict the two general sets of test conditions:

Group A: Experiments involving a relatively large burster charge ($40 \leq F/B \leq 53$) and a 150 ms time delay; and,

Group B: Experiments involving a relatively small burster charge ($73 \leq F/B \leq 88$) and a shorter 100 ms time delay.

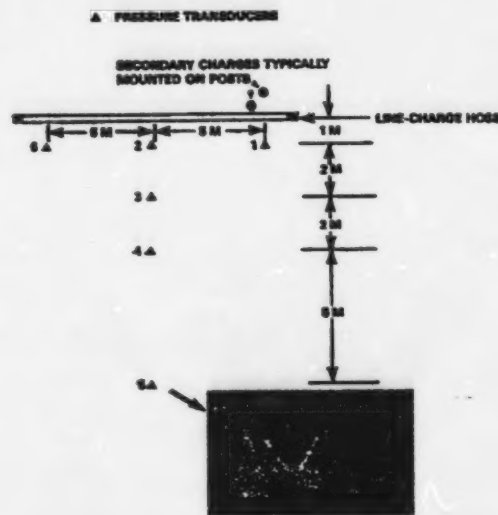


Figure 8: Pressure transducer array for line-charge tests

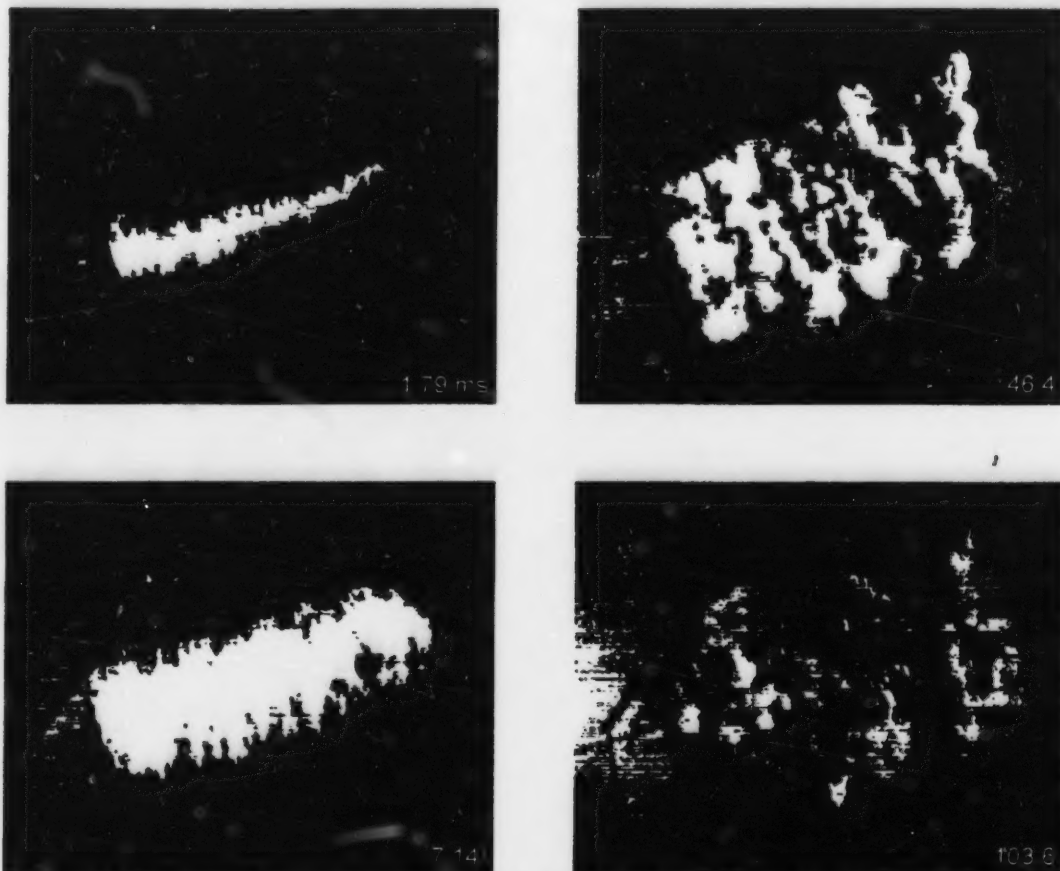


Figure 9: Selected frames from an overhead cinematographic record showing a developing droplet-air cloud. Indicated times are in ms.

A side-on cinematographic sequence showing successful fuel dispersal and propagation of detonation is presented in Figure 12. As shown in Table II, this type of sustained propagation was observed in 13 of 23 trials corresponding for the most part to the Group A parameter range. For those Group A tests in which satisfactory side-on and overhead cinematographic records were obtained, an estimate of the cloud volume was made from the contour plots by dividing the product of the cloud plan and profile areas by the cloud length. The results of this exercise, plotted in Figure 13 for clouds in the F/B range from 40 to 53, show the tendency toward globally stoichiometric composition as fuel dispersal progresses. Although the data suggest that the resultant clouds are somewhat lean in composition, it must be borne in mind that the above-described calculation assumes a rectangular cloud cross section and, as such, it tends to overestimate the cloud volume. Results of a similar exercise for Group B tests

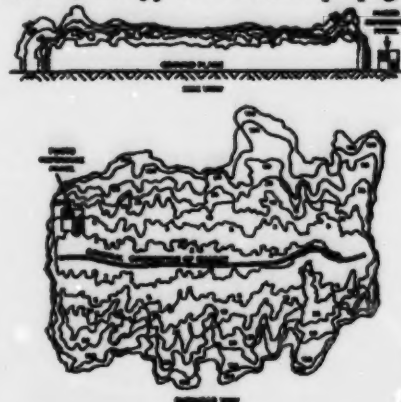


Figure 10: Side-on (top) and overhead (bottom) cloud contour plots for the event shown in Figure 9. Indicated times are in ms.

Table II
Summary of successfully executed line-charge trials

Trial No.	Hose Type	Hose Length (m)	Fuel Type ¹	Fuel-to-Burster Ratio (F/B)	Initiator Time Delay (ms)	Ambient Temp. (C)	Mean Detonation Velocity (m/s)
<i>A. Sustained Detonation</i>							
8524	Linen ²	30.5	PO	71	100	33	1900
8528 ⁴	Chem-Pet ²	30.5	PO	40	150	21	1570
8529	Linen ³	15.2	PO	47	150	21	1680
8558	GASynCHEM	15.2	PO	38	150	18	1760
8559	Covered Mill	15.2	PO	49	150	18	1820
8560	Chem-Pet	15.2	PO	40	150	6	1510
8561	Chem-Pet	30.5	PO	53	150	11	1460
8562	Six-Pass	30.5	PO	63	150	12	1630
8640	Redskin	15.2	PO	51	150	30	1100
8641	Chem-Pet	15.2	PO	53	150	27	1630
8644	Five-Pass plus	30.5	PO	54	150	24	1660
	Six-Pass plus	15.2		63			
	Burlington Fabric	15.2		56			
8651 ⁴	Red Chief	15.2	FFC	46	150	24	1810
8652 ⁴	HF-25	15.2	FFC	42	150	29	1480
<i>B. Partial Detonation</i>							
8531 ⁴	Chem-Pet	15.2	PO	40	150	20	1410
8553	Redskin	15.2	PO	77	100	11	1340
8555	Five-Pass	15.2	PO	88	100	16	1470
8556	Covered Mill	15.2	PO	73	100	17	1900
8557	Red Chief	15.2	PO	84	100	15	1540
8635	Chem-Pet	15.2	PO	40	100	30	1500
<i>C. Failure to Initiate Detonation</i>							
8550	Red Chief	15.2	PO	84	100	16	---
8552	Red Chief	15.2	PO	84	100	16	---
8646	Red Chief	15.2	FFC	91	150	26	---
8548	Chem-Pet	15.2	PO	87	150	25	---

¹ PO is propylene oxide; FFC is a code-named U.S. fuel

² lined with loose fitting polyethylene tubing

³ lined with bonded heavy rubber tubing

⁴ premature ignition occurred but did not affect the outcome

confirm that the combination of smaller burster charge and shorter time delay leads to clouds which are very fuel-rich and, consequently, of reduced detonation sensitivity. Thus, failure to initiate detonation is due to the secondary charges being too small.

A graphical summary of the test results is presented in Figure 14. Based on these data, the

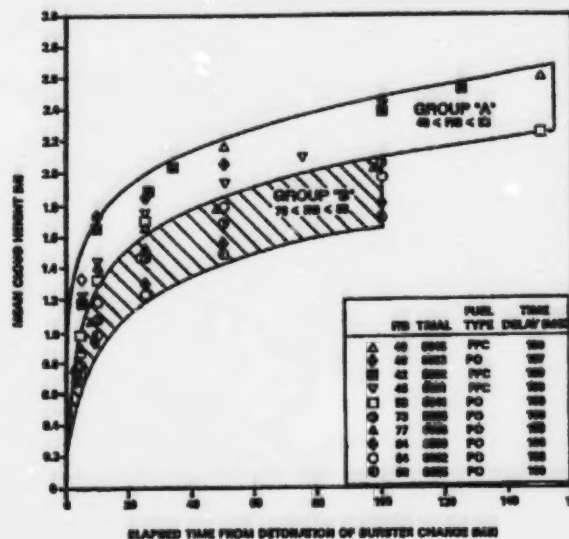


Figure 11: Cloud height from cinematographic records as a function of F/B and Δt

tests which employed a large burster, the detonation wave was seen to propagate several metres in that flank of the cloud containing the secondary charge before it was able to jump across the void to the opposite flank. Presumably, the jump became possible due to the existence of a corridor of favourable fuel-air mixture linking the flanks. In one such test, the detonation wave propagated the full length of the cloud in one flank prior to turning the corner and resuming propagation in the opposite direction. It is possible that the shock wave transmitted from the detonating flank to the unburned mixture in the opposite flank causes more complete atomization of the fuel droplets. However, this was not examined in any detail.

Several technical problems were encountered during the trials which led to unusable data. These tests are not listed in Table II. The most serious problem was that of premature ignition of the developing droplet-air cloud. In some cases, early ignition was observed near the ends of the line charge. This was due to the hot detonation products from the burster charge jetting out the ends of the fuel-filled hose. The problem was corrected by making the burster charge somewhat shorter than the hose (e.g., ~25

most reliable line-charge configuration involves a F/B ratio in the 45-55 range and a time delay of about 150 ms. This optimum F/B range is consistent with the value of 100 noted earlier for a cylindrical canister, bearing in mind that the ground plane in the line-charge geometry has the effect of approximately doubling the burster charge size.

One practical consideration which must be taken into account if these line charges are to be used in a minefield breaching role is that the droplet-air clouds consist of two distinct flanks, one on either side of the line-charge axis, with a void in the middle. A similar void exists when fuel is explosively dispersed from a canister to form a toroidal cloud. Based on the cinematographic records, the size of this void increases as the F/B ratio decreases (i.e., as the burster charge mass increases). In those

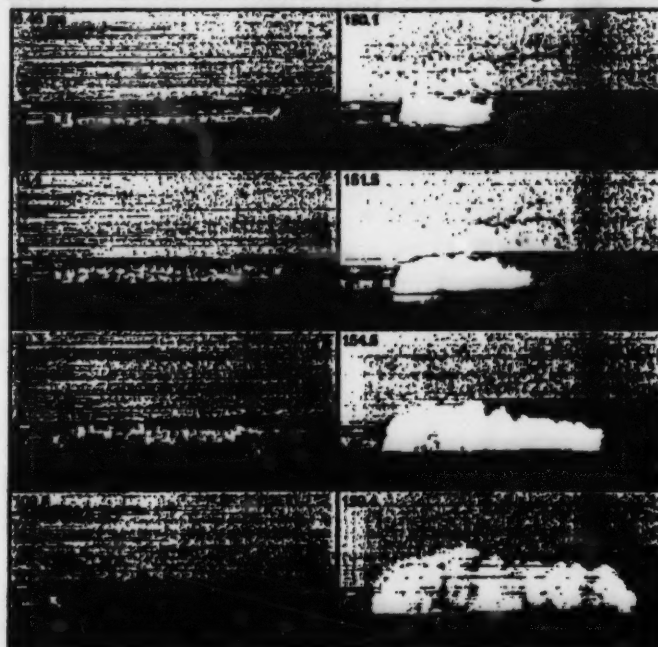


Figure 12: Selected frames from a side-on cinematographic record showing fuel dispersal and subsequent detonation. Indicated times are in ms.

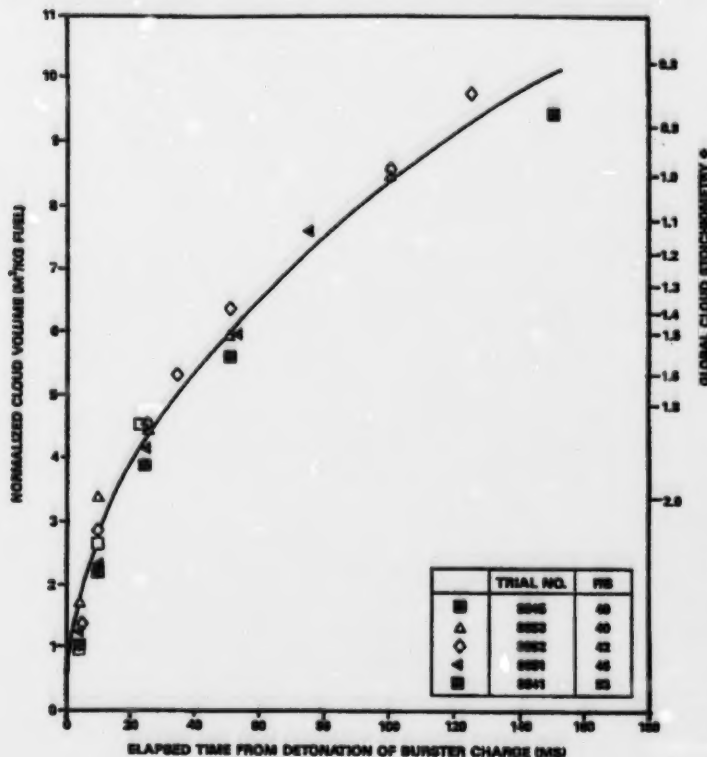


Figure 13: Normalized cloud volume from cinematographic records as a function of F/B and Δt

cord could be threaded. All designs performed satisfactorily. Our experience suggests that premature ignition can be prevented provided a layer of fuel at least 5 mm thick is present between the dispersal charge and hose wall.

Another technical problem encountered was failure of the detonation wave in the burster charge. This was traced to the existence of perforations in the polyethylene jacket of the detonating cord. It appeared that fuel was able to penetrate the explosive and reduce its sensitivity to detonation.

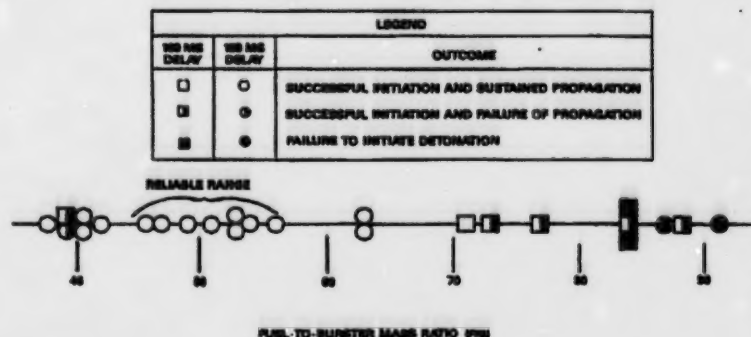


Figure 14: Summary of trials showing the optimum fuel-to-burster mass ratio for reliable detonation

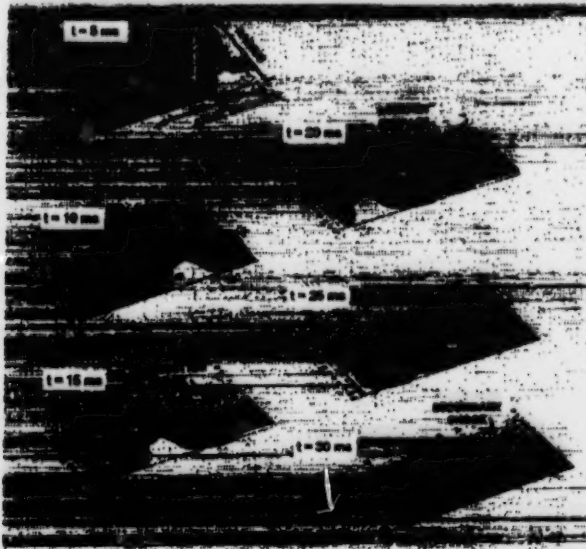


Figure 15: Carpet plots showing the predicted blast field generated by a detonating 4-m radius cloud of stoichiometric propylene oxide and air

distance from the initiation end of the cloud. The calculations reveal many of the finer details about the blast field including the locations of the contact surface, shock waves, and rarefaction waves. The pressure histories were monitored at several radial stations located nine cloud radii from the initiation end. These were integrated over the positive phase to obtain the impulse.

Peak overpressure and impulse as a function of range are summarized in Figures 16 and 17. Data from Moen and Ward^{2,12} for 45-mm diameter charges are included for comparison. Agreement between the predicted and observed overpressures is good at all stations except $R = 10$ m. At this location, the model consistently overpredicts the peak overpressures. The measured impulses are also less than the calculated ones, and considerably so at both $R = 1$ m and $R = 10$ m. Possible reasons for the poor agreement include: (i) the model cloud being thicker than the real one; (ii) the existence of the central void in the real cloud (hence, non-simultaneous detonation of the two flanks and also more rapid penetration of the rarefaction); and, (iii) poor dispersal and atomization of the fuel. Based on the available data, it is estimated that a 108-mm diameter hose would be needed to produce the levels of impulse calculated for the 4-m radius model cloud. In theory, however, this amount of fuel is sufficient

The blast produced by those clouds which were successfully detonated has been estimated using the previously-described numerical model developed by Combustion Dynamics Limited, except in this case the cloud takes the form of a hemi-cylinder and the detonation wave is marched from one end to the other. A cloud radius of 4 metres was used in the model because this is consistent with the observation from cinematographic records that the cross-sectional area of the most detonable clouds was about 25 m^2 . Not surprisingly, this radius is also fairly consistent with the stoichiometric cloud radius corresponding to the 2.7 kg/m^3 of fuel used in the line charges.

Results of the calculations are shown in Figure 15 in the form of three-dimensional, hidden-line "carpet" plots. Overpressure is plotted in the vertical direction as a function of radius and axial

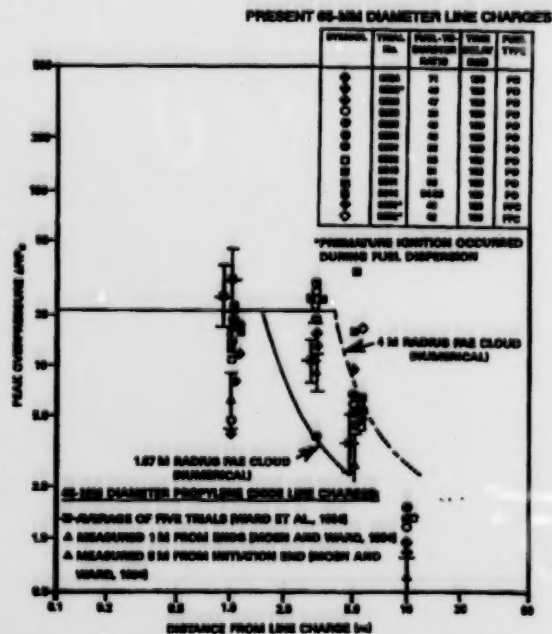


Figure 16: Peak overpressure versus range for propylene-oxide line charges

to produce a stoichiometric cloud having 2.5 times the volume of a 4-m radius cloud. Therefore, the "blast efficiency" of the real cloud (based on impulse) is only ~40%.

Figure 18 shows how the overpressure data for the 65-mm diameter line charge compares with those for a 7.56 kg/m high-explosive line charge as reported by Crepeau and Needham¹³. Note that the pressures within the FAE cloud are much lower than those generated by the HE line charge. However, outside the cloud the peak overpressures are comparable despite the fact that the HE charge is nearly three times the mass.

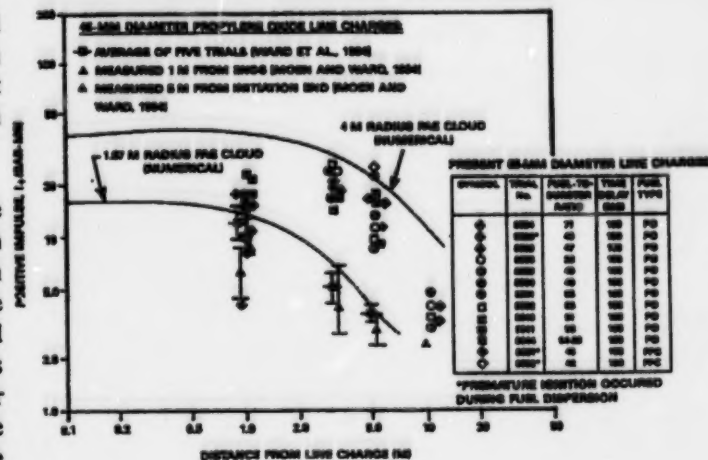


Figure 17: Positive impulse versus range for propylene-oxide line charges

The advantage of FAE over HE is emphasized in Figure 19 where the positive-phase impulses are compared. The impulse, and hence the mine neutralizing effectiveness in some critical areas (e.g., at $R = 1$ m, the likely path of vehicle wheels or tracks), is higher for FAE by as much as an order of magnitude.

2.3 Nitromethane Line Charges

Although the blast from an FAE detonation is sufficient to neutralize many types of simple, pressure-fuzed mines, it is not very effective against current generations of so-called "blast-resistant" mines. The nitromethane line charge discussed in this part of the paper was an attempt to combine the attractive features of HE line charges (i.e., high pressures) and FAE line charges (i.e., high impulses). Nitromethane is a monopropellant which can detonate in the liquid state or as a droplet-air cloud.

The first step in assessing the potential of this concept was to carry out numerical simulations similar to those performed for propylene-oxide line charges. These were done for a 100-mm diameter hose. Given this amount of energetic material (8.95 kg/m), the concentrations of nitromethane in

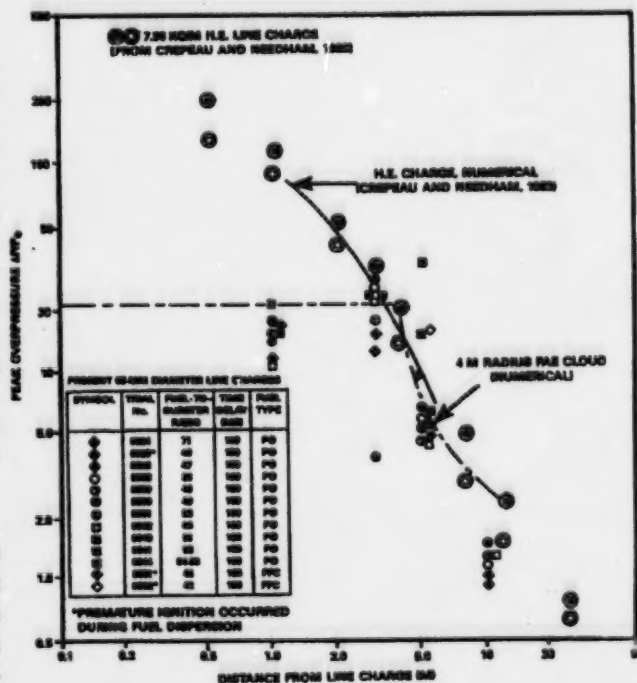


Figure 18: Comparison of peak overpressures for high-explosive and propylene-oxide line charges

clouds of various radii were first calculated. As in the earlier simulations, the clouds were assumed to be hemi-cylindrical in shape and of uniform composition. For this part of the study, the TIGER code¹⁴ was used to establish the detonation states of the explosive mixtures. The blast was then computed using the Combustion Dynamics Limited numerical model.

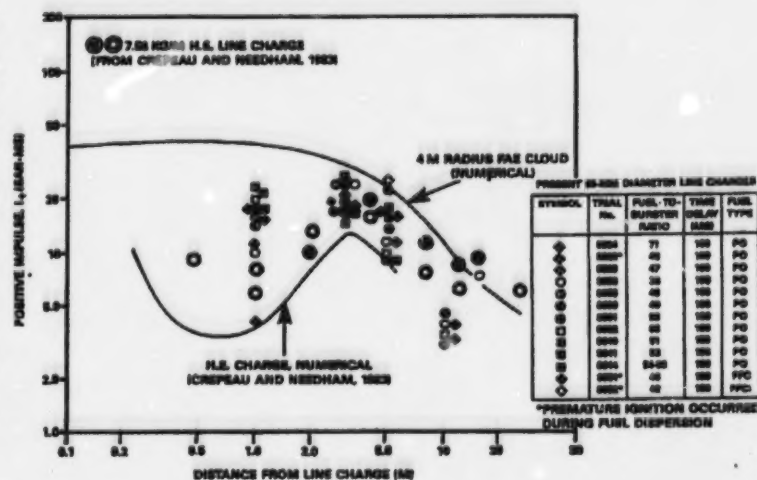


Figure 19: Comparison of positive impulses for high-explosive and propylene-oxide line charges

Results of the calculations are summarized in Figures 20 and 21

where the peak overpressure and impulse, respectively, are plotted against distance from the charge axis. It can be seen in Figure 20 that the detonation pressure increases as the cloud is made smaller for a fixed amount of nitromethane. A pressure of just under 200 atm is possible for a cloud of 1.0-m radius. This jumps to about 1000 atm if the cloud radius is reduced to 0.4 metres. Note that these pressures are 10 times and 50 times higher, respectively, than that possible with conventional FAE. It is of interest, however, that a higher detonation pressure does not guarantee higher pressures at all locations outside the cloud. From a pressure perspective, the 1.0-m radius cloud actually outperforms its 0.4-m radius counterpart over the range $0.5 \text{ m} \leq R \leq 1.2 \text{ m}$. A similar observation can be made about the impulse distributions. Figure 21 shows clearly how the skip zone becomes more predominant in the impulse profile as the cloud becomes progressively smaller (i.e., as the explosive medium approaches a high explosive).

The first practical issue to be addressed in the development of a nitromethane-based line charge was that of explosive fuel dispersal. In order to disperse nitromethane into a droplet cloud without a bulk detonation occurring, it was necessary to use a smaller burster charge and/or to encase

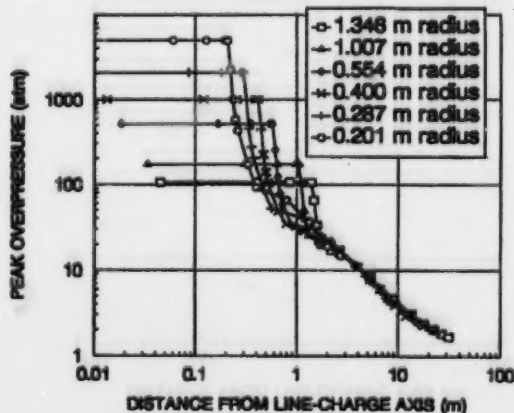


Figure 20: Calculated peak overpressures for 100-mm diameter nitromethane line charges

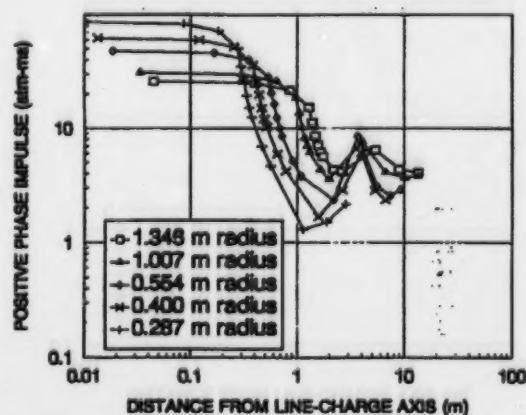


Figure 21: Calculated impulses for 100-mm diameter nitromethane line charges

it in a shock attenuating or "buffer" material. The buffer configurations investigated are shown in Figure 22. The first consisted of a dense rubber jacket of 3-mm thickness. The second candidate was a closed-cell foam rubber jacket having a wall thickness of 7 mm. The third buffer consisted of a combination of the first two. The detonating cord was first threaded through a rubber hose and the resultant assembly encased in a foam rubber sleeve. A series of 24 experiments employing line charges of 5- to 10-metre length was conducted to evaluate these charges. In some tests, the burster was allowed to float to the top of the fuel-filled hose (its natural tendency). In others, it was fastened to a steel cable so that it would sink. Selected tests employed a steel cable and a tethering arrangement to give the burster a 25-mm standoff from the bottom of the hose. The nitromethane was near room temperature for most tests.

The results of these experiments were straightforward. Explosive dispersal of nitromethane was found to be possible using: (i) a floating bare detonating cord of 21.3 g/m or less, (ii) a floating rubber-sheathed cord of 42.6 g/m or less, or (iii) a rubber-sheathed cord of 32.0 g/m or less positioned 25 mm from the bottom of the hose. The foam rubber jacket and the double-jacket designs were found to be unacceptable. The nitromethane was observed to detonate as a bulk explosive in every case. This was speculated to be the result of hot-spot phenomena related to the use of foam.

Having identified successful methods of dispersing nitromethane to form a droplet-air mass, a series of tests was carried out to determine if and how reliably such media would detonate. The line charges ranged in length from 5 to 10 metres. The secondary charge in all cases consisted of a 1-kg block of DM12 mounted on a post near ground level about 30 cm from the line-charge axis. Large secondary charges were used because the investigators had no idea what the critical charge mass would be for a "frothy" mixture of nitromethane and air. The time delays were varied between 5 and 30 ms. The combination of smaller Δt and larger F/B resulted in much smaller clouds than those generated for propylene-oxide fuel.

The results of these trials, summarized in Table III, show that detonation is possible for all values of Δt . The velocities of detonation (VOD) as measured from cinematographic records are also included for those trials in which the camera framing rate was high enough to permit an estimate to be made (and even in those cases the number of frames was small). The scatter in the VOD data is substantial.

Pressure measurements were made in a small number of the tests. Figures 23 and 24 show the peak overpressures and positive impulses generated by 10-m long line charges for a 5-ms time delay. Based on observations from the cinematographic records, the effective cloud radius (the clouds were not exactly hemicylindrical for a floating burster charge) at the time of initiation of detonation was just over a metre. Accordingly, the numerical predictions corresponding to cloud radii of 1.0 m and 1.35 m are included in the figures. The measured overpressures are in reasonable agreement with the predictions for small radii, but tend to fall short of the predictions as the distance from the charge increases. In view of the short charge lengths, this is likely due to the rarefaction

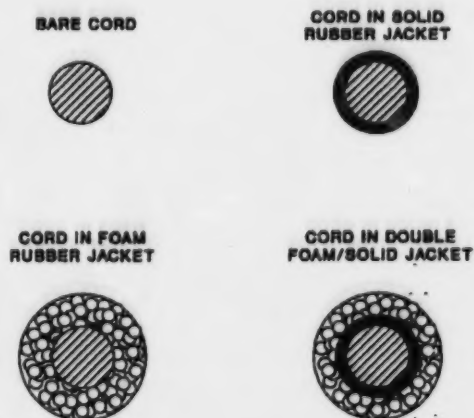


Figure 22: Burster charge configurations investigated for nitromethane dispersal

Table III
Summary of nitromethane droplet-air cloud initiation tests

Trial No.	Line-Charge Length (m)	Burster Configuration	Time Delay (ms)	Result and VOD (m/s)
9226	10	21.3 g/m; buffered; floating	5	Detonation; VOD = 4850
9247	10	21.3 g/m; buffered; floating	5	Detonation
9227	10	21.3 g/m; buffered; standoff ¹	5	Transition during dispersal ²
9062	7	32.0 g/m; buffered; floating	5	Detonation
9070	10	32.0 g/m; buffered; floating	5	Detonation; VOD = 3050
9071	10	32.0 g/m; buffered; floating	5	Detonation; VOD = 2960
9208	5	32.0 g/m; buffered; floating	5	Detonation; VOD = 4450
9235	10	32.0 g/m; buffered; floating	5	Detonation
9236	10	32.0 g/m; buffered; floating	5	Detonation
9238	10	32.0 g/m; buffered; floating	5	Detonation; VOD = 2460
9210	5	32.0 g/m; buffered; standoff ¹	5	Detonation; VOD = 4370
9217	5	32.0 g/m; buffered; standoff ¹	5	Detonation
9213	5	42.6 g/m; buffered; floating	5	Detonation; VOD = 3320
9248	10	21.3 g/m; buffered; floating	10	Detonation
9063	7	32.0 g/m; buffered; floating	10	Detonation
9209	5	32.0 g/m; buffered; floating	10	Detonation; VOD = 3920
9237	10	32.0 g/m; buffered; floating	10	Detonation
9246	10	32.0 g/m; buffered; floating	10	Detonation
9250	10	21.3 g/m; buffered; floating	15	Detonation
9245	10	32.0 g/m; buffered; floating	15	No data
9233	10	21.3 g/m; buffered; floating	20	Detonation; VOD = 2030
9249	10	21.3 g/m; buffered; floating	20	Deflagration
9239	10	32.0 g/m; buffered; floating	20	Detonation ³ ; VOD = 1450
9234	10	21.3 g/m; buffered; floating	30	Detonation; VOD = 2010

¹ Standoff was 25 mm from bottom of hose.

² Fuel dispersal was successful for the first 7 m followed by transition to bulk detonation.

³ Initiation of detonation in the cloud was marginal.

waves propagating inward from the ends. The measured impulses, however, are significantly higher than the predictions. This could be the result of late-time afterburning of the oxygen-deficient nitromethane as ambient oxygen becomes available.

The present experimental data indicate that a time delay considerably less than 5 ms will be required if high loading densities are to be achieved. In practice, however, this will lead to problems because of the different propagation velocities in the detonating cord and the droplet-air mass. What is really required is some means to guarantee a short but constant time delay between fuel dispersal and detonation. Along these lines, the authors have proposed a novel line-charge format consisting of a 100-mm diameter nitromethane-filled hose containing two detonating cords. One of these is a floating, rubber-sheathed, 21.3 g/m fuel dispersal charge. The second is a bare 85.2 g/m cord, laying at the bottom of the hose, intended to be a "travelling" initiation charge. This size of detonating cord is sufficient to initiate liquid nitromethane. Provided the detonating cords have identical VODs, it should be possible to maintain a fixed separation between the fuel dispersal wave and the lagging initiation wave. Given that the detonation velocity in the detonating cord is much higher than that which would normally exist in the droplet-air mass, the detonating cord will govern the propagation velocity in the mixture. One such test was conducted to assess the feasibility of this concept. A time delay of 1 ms was achieved by initiating the cords simultaneously but making the initiator cord 7 m longer than the fuel dispersal cord (the detonating cord VOD is ~7 m/ms). Cinematography confirmed that fuel dispersal was successful. However, the 85.2 g/m cord was found to be too small to initiate the partially dispersed mixture. The authors are of the opinion this concept warrants further study.

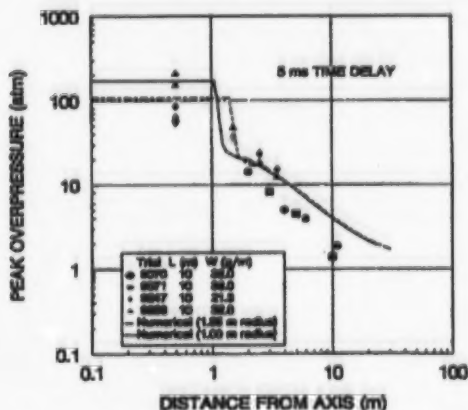


Figure 23: Comparison of predicted and measured peak overpressures for $\Delta t = 5$ ms

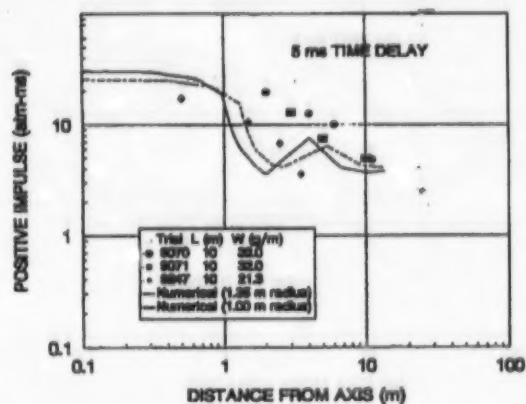


Figure 24: Comparison of predicted and measured positive impulses for $\Delta t = 5$ ms

3.0 CONCLUSIONS AND RECOMMENDATIONS

The critical high-explosive charge mass for direct initiation of spherical detonation in a globally stoichiometric, propylene-oxide, droplet-air cloud is about 8.5 g PETN. Based on earlier data for stoichiometric ethylene-air, these fuels have similar detonation sensitivities.

The optimum fuel-to-burster (F/B) mass ratio and initiation time delay (Δt) for 65-mm diameter propylene-oxide filled FAE line charges are 50 and 150 ms, respectively. The blast efficiency of the line charges in this study is about 40% based on a comparison between the measured and theoretically predicted positive impulses.

Higher detonation pressures are possible by replacing the propylene-oxide with more energetic nitromethane and by increasing the loading density via the use of a smaller fuel dispersal charge and a shorter initiation time delay. However, this gain in detonation pressure comes at the expense of

lower impulses at those locations which are of interest in a minefield breaching scenario. This result should not come as a surprise given that our intention was to develop an explosive charge residing somewhere between HE and FAE in performance.

Further work should be done to assess the potential of a proposed nitromethane line-charge design having a fuel dispersal charge and a separate "travelling" initiation charge.

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This paper describes the results of experiments to assess the potential of fuel-air explosive (FAE) line charges in minefield breaching operations. The line charge consists of a 65-mm diameter hose filled with a liquid hydrocarbon and fitted with an internal detonating cord referred to as the "burster" charge. When the detonating cord is initiated, the hose fragments and the fuel is propelled outward to form a large droplet-air cloud. The cloud is detonated a short time later by a high-explosive "secondary" charge.

The detonability of propylene oxide fuel is first determined in a series of tests employing FAE canisters of nominal 3-litre volume. The critical mass of secondary charge for direct initiation of spherical detonation in a globally stoichiometric droplet-air cloud is found to be 10 grams of DM12 (85% PETN) explosive, indicating that propylene-oxide-air and ethylene-air have similar detonation sensitivities.

The results of line-charge trials show that the optimum ratio of fuel mass to burster charge mass (the F/B ratio) is about 50 and that an initiation time delay (Δt) of 150 ms is most satisfactory. The blast efficiency of the line charges in this study is about 40% based on a comparison between the measured and theoretically predicted positive impulses.

Equilibrium and numerical calculations indicate that higher detonation pressures are possible by replacing the propylene-oxide with more energetic nitromethane and by increasing the loading density of the cloud. In practice, this is achieved by using a smaller burster charge and a shorter initiation time delay. However, this gain in detonation pressure comes at the expense of lower impulses at locations of importance in a minefield breaching scenario. This result is not surprising given that our intention was to develop an explosive charge residing somewhere between HE and FAE in performance.

One practical problem with nitromethane line charges is that the initiation delay is so short that the cloud size varies substantially along its length at the moment of detonation. A rather novel line-charge design having a fuel dispersal charge and a separate travelling initiation charge is proposed as a remedy. However, in the single experiment performed, the droplet-air mass did not detonate as a result of the initiation charge being too small. Further study of this concept is warranted.

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Burster Charge
Secondary Charge
Droplet Cloud
Droplet-Air Cloud
Initiation of Detonation
Pressure
Impulse
Detonability
Detonation
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Shock
Shock Wave
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